UNIVERSIDADE DE LISBOA

FACULDADE DE MEDICINA DENTÁRIA

COMPARATIVE ANALYSIS OF ROOT CANAL INSTRUMENTATION USING PROTAPER NEXT™, RECIPROC™ & WAVEONEGOLD™ SHAPE SYSTEMS

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“Quero, terei –

Se não aqui,

Noutro lugar que ainda não sei.

Nada perdi,

Tudo serei.”

Fernando Pessoa

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Eternamente grata.

RESUMO

INTRODUÇÃO: A Associação Americana de Endodontia define este ramo da Medicina Dentária como a ciência que se ocupa da morfologia, fisiologia e patologia da polpa dentária humana e das questões peri-radiculares. O seu estudo e prática, englobam ciências básicas como a biologia da polpa saudável e a etiologia, diagnóstico, prevenção e tratamento de doenças pulpares, associadas muitas vezes a condições de patologia peri-radicular. Tratamentos endodônticos de sucesso dependem de vários fatores, tais como o correto diagnóstico, limpeza, desinfeção e preparação canalares, tal como uma adequada obturação. O objetivo primário da preparação canalar inclui a remoção de substrato de matéria orgânica e detritos do sistema de canais, enquanto a anatomia original do mesmo é respeitada e mantida, para que possa haver, posteriormente durante a obturação, um eficaz preenchimento e selagem apical. A irrigação com soluções antibacterianas é um complemento indispensável à preparação mecânica, e depende largamente da habilidade desse mesmo irrigante em penetrar totalmente no sistema canalar. Essa penetração é influenciada pela anatomia original do canal, tal como pela preparação canalar obtida na instrumentação. Deste modo, a comparação e avaliação dos parâmetros dimensionais dos canais radiculares, antes e após a sua preparação mecânica, pelos diversos sistemas de limas presentes no mercado, torna-se essencial para obtermos, cada vez mais, tratamentos endodônticos de sucesso.

OBJETIVO: O propósito desde estudo *ex vivo* foi avaliar e comparar a preparação mecânica de canais radiculares, mesiais de primeiros molares inferiores humanos, utilizando os sistemas de limas rotatórios WaveOne Gold^{TM}, Reciproc^{TM} e ProTaper Next^{TM}. Para esta finalidade, avaliaram-se os seguintes parâmetros físicos: volume do canal, SMI e área de superfície (tridimensionais), e área e diâmetro médio do canal (bidimensionais).

MATERIAIS E MÉTODOS: Um total de 30 primeiros molares inferiores humanos, foram selecionados, sem qualquer identificação pessoal, e conservados numa solução de 0,5% de cloramina à temperatura ambiente, durante 48 horas e seguidamente lavados em água corrente. O operador, que desenvolveu também o restante estudo e tese de mestrado, foi uma aluna do último ano de Medicina Dentária da Universidade de

Lisboa. As coroas dos dentes foram cortadas aproximadamente ao nível da junção amelo-cementária, deixando apenas 2 milímetros da câmara pulpar, e as raízes distais removidas com a ajuda de uma turbina. Cada raiz mesial foi colocada num tubo de Eppendorf com 1 mililitro de solução salina, para que se mantivessem hidratadas. Restos de tecidos ou calcificações foram removidos com uma ponta destartarizadora. Os fatores de exclusão de possíveis amostras foram os seguintes: raízes com ápex aberto, canais sem permeabilidade, raízes com ângulos acentuados ou canais calcificados, canais com tratamento endodôntico realizado, fraturas e cáries radiculares, nódulos pulpares e reabsorções internas. Todas as amostras foram analisadas antes e depois da instrumentação canalar, por um aparelho de micro tomografia computorizada (SKYSCAN 1174 v.2 - Kontich, Bélgica), em colaboração com o "Centro para o Desenvolvimento Rápido e Sustentável do Produto – Instituto Politécnico de Leiria", e registados todos os dados e imagens. Após a primeira captação de imagens, as amostras foram preparadas mecânica e aleatoriamente, em grupos de 10, de acordo com as técnicas recomendadas pelos fabricantes. O comprimento de trabalho foi determinado introduzindo limas manuais K-10 (Dentsply-Maillefer, Ballaigues, Switzerland) nos canais até serem visíveis no forame apical. A esse valor foi retirado meio milímetro. A via de permeabilidade foi conseguida com recurso ao sistema rotatório Proglider® (Dentsply-Maillefer, Ballaigues, Switzerland) e a irrigação feita com uma solução de 10% de ácido cítrico. A instrumentação foi concluída com as limas correspondentes ao diâmetro apical de 0,25mm, em cada um dos sistemas: lima primária no WaveOne Gold™ (grupo A), R25 no Reciproc™ (grupo B) e X2 no ProTaper Next™ (grupo C). Na análise estatística, com recurso ao programa IBM SPSS versão 23.0, foi feita uma análise descritiva inicial para cada grupo em estudo. As variáveis com distribuição normal foram testadas com One-Way ANOVA e testes Bonferroni post-hoc. As variáveis que rejeitaram distribuição normal foram testadas com Kruskall Wallis (não paramétrico). O nível de significância foi padronizado em 0.05. A informação teórica para este estudo foi encontrada em livros, da Biblioteca da Faculdade de Medicina Dentária da Universidade de Lisboa, e em pesquisas online no motor de busca PubMed, com acesso à base de dados MEDLINE, com as seguintes palavras-chave: "endodontics", "root canal shaping", "WaveOne Gold", "ProTaper Next", "Reciproc", "rotary instruments" and "micro computerized tomography". Foram encontrados cerca

de 2000 artigos, dos quais se revelaram com interesse e dentro dos fatores de inclusão para o presente estudo, apenas 34. Os critérios de exclusão foram: artigos com acesso limitado mediante pagamento, estudos em modelo animal, artigos em idiomas para além do inglês ou português, e artigos publicados há mais de 40 anos.

RESULTADOS: Após a avaliação das preparações mecânicas feitas pelos 3 sistemas de limas em estudo, WaveOne Gold™, Reciproc™ e ProTaper Next™, comparando os parâmetros: volume do canal, SMI, superfície, área do canal e diâmetro médio, os resultados foram os seguintes: nos parâmetros tridimensionais (volume, SMI e superfície canalares) não se verificaram diferenças estatisticamente significativas entre os 3 sistemas (p-value > 0,05); nos parâmetros bidimensionais, sim: ao nível da área, verificou-se um aumento estatisticamente significativo apenas no sistema Reciproc; ao nível do diâmetro, o sistema Reciproc revelou, novamente, um aumento significativo em relação ao sistema ProTaper Next, mas sem diferença estatística para o sistema WaveOne Gold.

DISCUSSÃO: A utilização de dentes humanos naturais extraídos, em estudos de natureza endodôntica, tem a vantagem de reproduzir as condições clínicas. Contudo, a variabilidade morfológica dos sistemas de canais radiculares num mesmo grupo de dentes, torna bastante complexa a sua padronização. A nossa amostra inicial, não revelou, no entanto, na análise estatística, significantes diferenças anatómicas entre os 3 grupos em estudo, sendo, portanto, um bom ponto de partida. Para além disso, perderam-se duas amostras durante o estudo: a amostra 16 fraturou na captação de imagens na micro tomografia computorizada, e a amostra 20 não tinha permeabilidade canalar. Assim sendo, a amostra total final foi de 28. Em geral, face à dificuldade em obter dentes dentro dos critérios pretendidos, a amostra do nosso estudo é relativamente reduzida. No entanto, outros estudos semelhantes, utilizaram amostras quantitativamente semelhantes. Os resultados ao nível do SMI, parâmetro que permite quantificar a forma tridimensional de uma estrutura, revelaram-se dentro do esperado, em média próximos de 4, refletindo a conicidade dos instrumentos rotatórios utilizados, que conferem características circulares às preparações canalares realizadas. O aumento da área e diâmetro canalares verificados nos sistemas Reciproc™ e WaveOne Gold™ (este último apenas ao nível do diâmetro), poderá constituir uma vantagem ao nível da penetração do agente irrigante antibacteriano, que assim, mais facilmente percorrerá

todo o sistema canalar e atuar eficazmente a nível químico, complementando a ação mecânica das limas na fase de instrumentação canalar. Embora, as limas finais dos 3 sistemas em estudo tenham o mesmo diâmetro apical, ISSO 25, a sua conicidade é diferente, sendo uma possível explicação para os resultados obtidos. A utilização da técnica de captação de imagem com micro tomografia computorizada, teve como vantagens a sua alta-resolução, imagens tridimensionais e de vários ângulos, medidas detalhadas qualitativa e quantitativamente, e ser uma técnica não invasiva/destrutiva. No entanto, é um método muito caro, que necessita de equipamentos e profissionais tecnicamente habilitados, e cuja captação de imagem pode ser demorada. Este método é uma referência para estudos *ex vivo*, contudo não é aplicável a nível clínico.

CONCLUSÃO: Em geral, pode admitir-se que o sistema Reciproc™ foi o que produziu as alterações geométricas mais significativas ao nível dos canais radiculares em estudo, seguido pelo sistema WaveOne Gold™ e ProTaper Next™, respetivamente. Não existem, até à data deste estudo, artigos que avaliem os modernos instrumentos rotatórios WaveOne Gold™, e assim sendo, as conclusões são limitadas. Estudos adicionais envolvendo estes sistemas de limas endodônticas são necessários para que mais e melhor informação possa ser adquirida e transmitida, permitindo aos Médicos Dentistas, durante a sua prática clínica, adaptar cada sistema rotatório a um caso clínico específico.

Palavras-chave: endodontia; instrumentos rotatórios; instrumentação canalar; micro tomografia computorizada; WaveOne Gold; Reciproc; ProTaper Next.

ABSTRACT

INTRODUCTION: Root canal therapy is one of the most widely accepted treatment modality for pulpally involved teeth. Objective in root canal preparation is to develop a shape that tapers from apical to coronal, maintaining the original canal anatomy. Irrigation with antibacterial solutions is performed as complement to mechanical preparation and it depends largely on the ability of the irrigant to penetrate the full extent of the root canal system, influenced by the original anatomy as well as the final shape created through mechanical preparation.

AIM: The purpose of this *ex vivo* study was to evaluate and compare the mechanical preparation of three different rotary file systems: WaveOne Gold™, Reciproc™ and ProTaper Next™. Analyzed with computerized micro tomography, the following parameters were evaluated: canalar volume, SMI, surface, area and diameter (average).

MATERIALS AND METHODS: A total of 30 extracted humans mandibular first molars were selected. Each mesial root was, randomly, placed separately and prepared, by the same operator, in three groups of 10 samples: Group A – WaveOne Gold™, Group B – Reciproc™, Group C – ProTaper Next™. An image analysis, and data register, was made before and after the canal instrumentation, using micro-CT (in collaboration with CDRsp - IP Leiria).

RESULTS: There are statistically differences in the post instrumentation bidimensional parameters**: t**he area increase with Reciproc files was significantly greater than with WaveOne Gold ($p = 0.026$) or Protaper Next ($p = 0.007$); the diameter increment after the preparation with Reciproc files was significantly higher than with ProTaper Next ($p = 0.032$), however, the difference between Reciproc and Wave One Gold was not statistically significant.

DISCUSSION AND CONCLUSION: The Reciproc files produce major changes in the geometric conditions of the root canal systems, followed by WaveOne Gold and ProTaper Next, respectively.

KEYWORDS: endodontics; root canal shaping; WaveOne Gold; ProTaper Next; Reciproc; rotary instruments; micro computerized tomography.

1. INTRODUCTION

1.1 Endodontics – definition and aims

The American Association of Endodontics defines Endodontics as "the branch of dentistry concerned with the morphology, physiology and pathology of the human dental pulp and periradicular tissues; it's study and practice encompass the basic and clinical sciences including the biology of the normal pulp and the etiology, diagnosis, prevention and treatment of diseases and injuries of the pulp and associated periradicular conditions." (AAE 2012)

Root canal therapy is one of the most widely accepted treatment for pulpally involved teeth. Successful endodontic therapy depends on many factors like correct diagnosis, effective cleaning, shaping and disinfection of the root canals, and on adequate obturation (Mehran, 2008). The primary objective of canal preparation includes removal of organic substrate from the canal system into a continuously tapering preparation while maintaining the original outline and form of the canal (Schelder, 1974). This is one of the most important steps in any root canal treatment, following the original shape of the canal (Dhingra et al. 2015). The configuration for prepared root canals should be a conical tapered canal with the smallest diameter and a marked stop at the apical constriction. As root canal curvature increases, more difficult is to have an adequate canal preparation (Shäfer et al. 1996).

1.2 Evolution of mechanical rotary instruments

Due to their flexibility and elasticity, nickel-titanium (NiTi) instruments have been introduced into the endodontic armamentarium to facilitate the instrumentation of curved canals and with rotary techniques improve root canal preparation, with their unique properties: able to improve morphological characteristics and safety of canal shaping (Bergmans et al. 2003). Rotary files can prepare root canals faster, easier and at the same time, preserve the original canal shape with considerably less iatrogenic errors (Capar et al. 2014). It has been reported that they can maintain the original shape of canal with minimal transportation (Bryant et al. 2005). Irregularities in the root canal system can restrict the complete debridement of root canal by mechanical instrumentation. Irrigation serves as a flush to remove debris and smear layer, tissue solvent, eliminate pulpal tissue, bacteria and endotoxins, and as a lubricant (Chan et al. 1996).

1.2.1 M-Wire NiTi alloy

Instruments manufactured from M-wire NiTi alloy improve file flexibility and resist cyclic fatigue while retaining cutting efficiency (Alapati et al., 2009). They're instruments made of a special metal alloy, which undergoes alternate cycles of cold and heat during manufacture, which provides a significant increase in their flexibility and mechanical strength (Kim et al. 2012). NiTi rotary instruments are important in endodontics because of their ability to shape root canals with minimum complications (Young et al., 2007). As the rotary NiTi instruments maintained the original canal curvature, particularly in the apical region of the root canal better than stainless steel hand instruments, studies compared the shaping ability of different rotary NiTi systems with different designs. With advent of instruments manufactured from nickel titanium alloys (NiTi), there was significant improvement of quality of root canal shaping, with predictable results and less iatrogenic damage, even in severely curved canals (Peters OA, 2004).

1.2.2 Gold-Wire – The new supermetal

Engineers have identified the desired phase-transition point between martensite and austenite that serves to produce a more clinically optimal metal than NiTi itself. This thermal process and post-machining procedure have generated a new supermetal that is commercially termed Gold-Wire. Specifically, the Primary WaveOne Gold^{TM} file is at least 80% more flexible, 50% more resistant to cyclic fatigue, and 23% more efficient, compared to its Primary WaveOne M-Wire predecessor (data on file: Dentsply Maillefer engineering and testing; Ballaigues, Switzerland, 2014). The new patented cross section and supermetal serve to improve shaping results in anatomically longer, narrower, and more apically curved canals, while decreasing the potential for iatrogenic events (Clifford JR, 2016).

1.2.3 Reciprocating motion

The use of reciprocating motion may be considered as a recent innovation in mechanized root canal instrumentation; with its differentiated kinematics being described as an oscillatory movement in which the instrument turns in the clockwise direction, and then counter-clockwise before completing a full 360º rotation cycle (Gavini et al. 2012). Reciprocating instruments have been developed to reduce the stress that rotary instruments suffer, particularly during the preparation of curved canals (Varela-Patiño et al., 2010). The use of reciprocating motion can extend the lifespan of a NiTi instrument and allow it to resist fatigue better than it can with continuous rotation (You et al., 2010).

1.2.4 Single-file shaping technique

Single file rotary systems are gaining clinical acceptance as they reduce the time required for biomechanical preparation, as well as reduce the number of failures related to instrumentation (Bürklein et al., 2012**)**. This single-file systems concept, used either in a reciprocal motion or in continuous rotation, provide a shaping technique, regardless of the length, diameter, or curvature of any given canal. In fact, it has been shown that a single-file shaping technique is more than 4 times safer and almost 3 times faster than using multiple rotary files to achieve the same final shape (Gambarini et al., 2010; You SY, et al., 2010). In previously studies, single-file reciprocating system strongly decrease the mean preparation time in comparison with multi-file rotational system (Bürklein et al., 2012) and, so, thee time available for chemical disinfection of the root canal system is also simultaneously increased.

1.3 Rotary instruments

The aim of this study was to evaluate the mechanical preparation of natural root canals with three different rotary systems:

1.3.1 The WaveOne Gold^{TM} (Dentsply Tulsa Dental Specialties) system is a single-file and single-us technique. Through the convergence of an advanced design, Gold-wire technology, and a unique reciprocating movement (170º counterclockwise motion followed by 50º clockwise rotation), preparing canals is safer, easier and faster than with WaveOne (at least 80% more flexible, 50% more resistant to cyclic fatigue, and 23% more efficient, compared to the original Primary WaveOne M-wire file). There are 4 WaveOne Gold files available in various lengths to more effectively address a wider range of endodontic anatomy compared to its WaveOne predecessor. The 4 files are termed: Small (yellow 20/07), Primary (red 25/07), Medium (green 35/06), and Large (black 45/05). The Small 21/06 file has a fixed taper of 6% over its active portion. Each file has a fixed taper from D1-D3, yet a progressively decreasing percentage tapered design from D4-D16, which serves to preserve dentin. For example, the Primary file has diameters of 0.85 mm and 1.0 mm at D9 and D12, respectively, or the length this file typically extends below the orifice during canal preparation. Fortuitously, the Primary 25/07 file is generally the only file required to fully shape virtually any given canal. (Clifford J. Ruddle DDS - Advanced Endodontics)

Figure 1 – WaveOne Gold^{TM} system

1.3.2 The Reciproc™ (VDW, Munique, Germany) system consists of 3 files with a fixed taper over the first 3mm from the tip: R25 (size 25 tip and .08 taper) for narrow canals, R40 (size 40 tip and .06 taper) for medium canals, and R50 (size 50 tip and .05 taper) for wide canals, characterized by an S-Shape cross-section, specifically designed for curved and narrow canals (Dhingra et al., 2015). Reciproc files provide clockwise (150º) and counterclockwise (30º) rotation. As, the rotation in the cutting direction is larger than reverse direction, it results in movement towards apex. Only one instrument is used for the canal preparation depending on the initial size of the canal. The instruments are made from an M-Wire nickel-titanium that offers greater flexibility and resistance to cyclic fatigue than traditional nickeltitanium. They have an S-shaped cross-section with sharp cutting edges (Bürklein et al., 2012). Only very light apical pressure should be applied on the instrument, as it's advancement would be almost automatic.

Figure 2 – Reciproc™ system (Dentsply-Maillefer, Ballaigues, Switzerland)

1.3.3. ProTaper Next™ (Dentsply-Maillefer, Ballaigues, Switzerland) is a NiTi system manufactured using M-wire Ni-Ti alloy (Sportswire, Langley, OK). The files have an off-centered rectangular cross-section, giving a snake-like swaggering movement as it moves along the root canal, thus reducing the screw effect, the unwanted taper lock and torque on any of the given file; thus decreasing the file-root dentin contact (Ruddle CJ, 2001). The ProTaper Next system is composed by five files with the same rectangular cross section, off-centered, intended to reduce torsional stress on the instrument: X1, X2, X3, X4 and X5, all in different lengths – 21, 25 and 31mm (Files X1 and X2 are used for shaping, and Files X3, X4 and X5 are optional). The off-center rectangular cross section differs from the center of mass. Only two points of the cross section touch the canal wall at a time, reducing the torsional stress on the file. The result is a fully-tapered and predictable shape achieved with greater procedural efficiency. This rotary file system is used in a rotary movement with slow in-and-out motions using an endodontic micromotor at 300rpm and 2N/cm torque settings (Dentsply Maillefer).

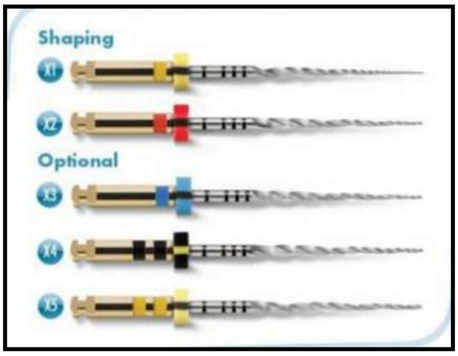


Figure 3 – ProTaper Next™ system (Dentsply-Maillefer, Ballaigues, Switzerland) is composed by five files: X1, X2, X3, X4 and X5.

1.4 Mandibular first molar – anatomy

The mandibular first molar usually has two roots (99,2%) – mesial and distal, but occasionally three, with two canals in the mesial (96,8%) and one or two canals (both with 49,8% - and three canals with 0,4% probability) in the distal root. The canals of the distal root are larger than those of the mesial root, and easier to locate. The mesial root of mandibular first molars has one of the most complex internal anatomies in the human dentition, due to the high prevalence of curvatures, isthmuses, fins and multiple canals that join and separate at different levels of the root (Villas-Boas et al. 2011). The mesial roots are usually curved, with the greatest curvature in the mesiobuccal canal, opening under the mesial cusps (Cohen et al. 2015; Nur et al. 2014). Because of this complex configuration, this root has been the focus of several anatomical studies using methods that include plastic resin injection, radiography, histology, scanning electron microscopy, conventional computed tomography (CT) and clearing of samples with ink injection (de Pablo et al. 2010).

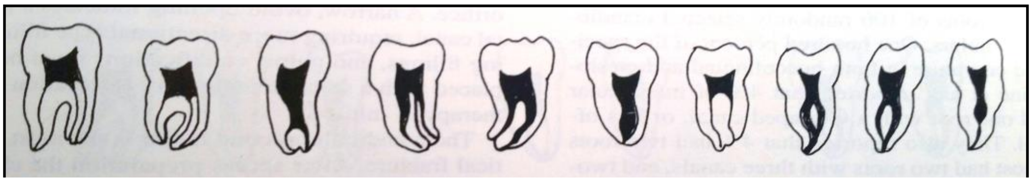


Figure 4 – Variability of canals systems in mandibular first molar (Cohen et. Al, 2015)

1.5 Image Analysis – Computerized micro tomography (µTC):

High-resolution micro-computed tomography is an innovative technology with several applications in endodontic research and education. Conventional X-ray computed tomography (CT) is an imaging modality that was first described by Hounsfield (1973). This technique produces a series of images through tomography or imaging by sections, which are then reconstructed three-dimensionally using computer software programs (Hounsfield, 1973).

The possibility of traditional CT application in endodontics to three-dimensionally reconstruct teeth was first explored by Tachibana and Matsumoto (1990). While these investigators were able to demonstrate anatomical configuration of teeth using CT, the spatial resolution of 0.6 mm was found to be insufficient to allow for detailed analysis of root anatomy and structures. The authors concluded that conventional CT offered only limited application in endodontics due to its high radiation dose, time consumption, cost, insufficient resolution, and inadequate computer software capability. However, some investigators (Velvart et al., 2001) still found traditional CT useful compared to periapical radiographs when planning for periapical surgery of mandibular molars and premolars.

Other technological advancements allowed for the introduction of a miniaturized form of traditional CT, the micro-CT (Kak and Stanley, 1988) for use in nonclinical settings. Micro-CT applies comparable principles to those of conventional CT, but the three-dimensional reconstructions of small objects, such as teeth, are developed to a resolution of within a few microns (<2 µm for Scanco µCT50, SCANCO Medical, Switzerland). While initial investigations using micro-CT technology were hampered by limited vertical resolution capacity of 1–2 mm (Dowker et al., 1997; Nielsen et al., 1995), improvements in the micro-CT machinery and computer software employed in reconstruction of images have allowed for significantly more accurate analysis of root canal systems (Dowker et al., 1997; Peters et al., 2000, 2001).

2. AIM

The purpose of this *in vitro* study was to evaluate and compare the mechanical preparation of mesial root canals of mandibular first molars, using three different file systems: ProTaper Next™ (Dentsply Maillefer, Ballaigues, Switzerland), Reciproc™ (VDW, Munich, Germany) and WaveOne Gold™ (Dentsply Tulsa Dental Specialties). Using computerized micro tomography (μTC), the following parameters were evaluated: 3D parameters: 1. Canal Volume, 2. SMI, 3. Canal Surface; 2D: 4. Canal Area and 5. Average canal diameter. To achieve this objective, the following experimental hypotheses were formulated:

- ✓ H0: There is no statistically significant difference between the three mechanical canalar instrumentation systems using mesial root canals of mandibular first molars in the parameters in study;

- ✓ H1: There are statistically significant differences between the three mechanical canalar instrumentation systems using mesial root canals of mandibular first molars in the parameters in study.

3. MATERIALS AND METHODS

3.1 Sample preparation teeth

A total of 30 extracted humans mandibular first molars were selected, without identification, kept in a 0.5% chloramine solution at room temperature for 48h, and next, washed in running water. The operator is a final year student of the course of Dentistry at the University of Lisbon, who led the study and the master's thesis. The crowns were eliminated by the lap, leaving 2mm of the pulp chamber, with an Isomet 1000 precision saw (Buehler, Lake Bluff, IL, USA) equipped with a 0,3mm diamond disc (Buehler) and water cooling. The distal roots were split with a tapered drill turbine at high speed and water. Each mesial root was placed in an Eppendorf vial with a saline solution (1mL) to keep hydrated. To each root/vial was add a specific number (1 to 30). Tissue fragments and calcified debris were removed from the teeth by ultrasonic scaling. The following were determined as exclusion factors: roots with open apex, without permeable canals, roots with right angles or calcified canals, with endodontic treatment, root fractures, root caries, root restorations, pulp nodules and internal resorption. An image analysis was made before and after the canal instrumentation, using micro-CT.

3.2 Tridimensional images with Computerized Micro Tomography (µTC):

In collaboration with "Center for rapid and sustainable product development - Instituto Politécnico de Leiria", was used X-ray micro-CT SKYSCAN model 1174 v.2, Software version 1.1 (SkyScan, Kontich, Belgium). This scanner uses an x-ray source with adjustable voltage and a range of filters for versatile adaptation to different object densities. A sensitive 1.3-megapixel x-ray camera allows scanning of your whole sample volume in several minutes. Variable magnification (6-30 µm pixel size) is combined with object positioning for easy selection of the object part to be scanned. The scanner can run from any desktop or portable computer, requiring just one USB (or serial) port and a FireWire (IEEE1394) input. The full range of SkyScan software is supplied, including fast volumetric reconstruction, software for 2D/ 3D quantitative analysis and for realistic 3D visualization (Brochure Bruker Micro CT Academy, 2015).

In this study micro-CT was used with appropriate parameters for scanning each root, pre and post instrumentation: each image pixel size is 22.70 µm; image rotation is 0.2000; source Voltage 50kV and source Current 800µA; exposure 8500ms; sharpening 40%; rotational step of 1.500º (degrees); rotational angle of 187.50º; average exposure time of 55 minutes.

The reconstruction of de images was made with NRecon program, version 1.6.8.0 (SkyScan, Kontich, Belgium), in standard reconstruction mode. Each image has 752 x 752 pixel; smoothing 0 (scale 0-10); ring artifact correction 6 (scale 0-20); beam hardening correction 45% (scale 0-100); lower grey threshold between 58 and 70; and upper grey threshold always 255.

At the end of each image analysis, a record was made of the values obtained for each parameter studied. The tables are attached (see appendix 2).

Figure 6 – Computorized Micro Tomography (IPLeiria)

3.3 Canal instrumentation:

The mesial root canals of the mandibular first molars were prepared, by the same operator, in three groups of 10 (A, B and C), randomly, using the technique recommended by the manufacturer. Working length was determined by advancing a size 10K-file (Dentsply-Maillefer, Ballaigues, Switzerland) into the canal until it is just visible at the apical foramen. Adjusted the stop to the top of the root and the value of the working length was the measurement value of that length minus 0.5mm. The permeability pathway was achieved using the Proglider® rotary instruments (Dentsply-Maillefer, Ballaigues, Switzerland). The Proglider® NiTi rotary instrument is manufactured using M-Wire NiTi alloy to enhance flexibility and cyclic fatigue resistance as claimed by the manufacturer. The system consists of a single instrument, with a variable progressive taper. The Proglider® instrument is available in 21, 25 (used) and 31 mm length and tip size 16 with a taper of .02 (10). Canals was irrigated during preparation using a citric acid 10% solution in a disposable plastic syringe.

- ✓ **Group A – WaveOne Gold™** (Dentsply Tulsa Dental Specialties) instruments were used with a dedicated reciprocating motor – "WAVE ONE ALL" mode with 170º counterclockwise motion followed by 50º clockwise rotation with a speed of 350 rpm. The shaping procedure was done with the Primary file (025/07 red, taper .08), using gentle inward pressure and letting passively progress through any region of the canal that has confirmed glide path. After shaping 2-3mm of any given canal, the Primary file was removed and cleaned. Irrigate, recapitulate with a size 010 hand file, and re-irrigate. Then, used the Primary file, and continued in 2-3 passes, to the full working length.

- ✓ **Group B - Reciproc™** (VDW, Munique, Germany): R25 file was used in a programmed reciprocating motion generated by the electric motor (Tecnika, Dentsply Maillefer, Schools Grant Program) in the "RECIPROC ALL" mode with 150º counterclockwise motion followed by 30º clockwise rotation with a speed of 300rpm. The were used in a pecking motion (amplitude less than 3mm, 3 pecks) according to the manufacturer's instructions. (R25: diameter 0,25mm; taper .08)

- ✓ **Group C - ProTaper Next™** (Dentsply-Maillefer, Ballaigues, Switzerland): This rotary file system was used in a rotary movement with slow in-and-out motions using an endodontic micromotor at 300rpm and 2N/cm torque settings. The sequence was: X1 instrument at working length, X2 instrument at WL (taper .06). For each root canal, a new set of ProTaper Next instruments was used.

Figure 5 – Electric motor (Tecnika, Dentsply Maillefer, Schools Grant Program)

3.3 Statistical analysis

The statistical analysis was carried out using the IBM SPSS 23.0 software. Descriptive analysis was first performed for each group. Sample means and sample standard deviations were calculated and boxplots were constructed. Normality and homoscedasticity were tested using Shapiro-Wilk test and Levene's test respectively. Clearly defined outlier candidates which altered distribution were removed and sample means and standard deviations adjusted.

Variables with normal distribution allowed testing for differences among group means with One-Way ANOVA and Bonferroni post hoc-tests. In the cases where homoscedasticity was not verified, a Welch ANOVA was carried out along with a Games-Howell post-hoc test.

The statistical testing was performed on the differences registered after canal preparation, as well as the measurements before canal preparation.

Non-parametric test Kruskall Wallis was performed on variables which rejected normal distribution. Significance level was set at 0.05 throughout the analysis.

3.5 Bibliographic research

For this work, a literature search was carried out by scientific articles and books. The online search was made in Pub-med, using the following keywords: “endodontics”, “root canal shaping”, “WaveOne Gold”, “ProTaper Next”, “Reciproc”, “rotary instruments” and “micro computerized tomography”. The selected articles were published in the last 40 years and written in English. I met around 2000 articles of which used 34 that met the inclusion criteria described above. Exclusion criteria were paid articles, research in animal models or articles that did not cover directly the article under consideration.

4. RESULTS

The results of the experimental procedure are shown in the following tables, with the parameters analyzed in the study (1. Volume (µm^3), 2. SMI, 3. Surface (µm^2), 4. Area (µm^2), 5. Diameter Average (µm)), before and after canal instrumentation, and compared the results between the 3 files systems under study (1. WaveOne Gold, 2. Reciproc, 3. ProTaper Next).

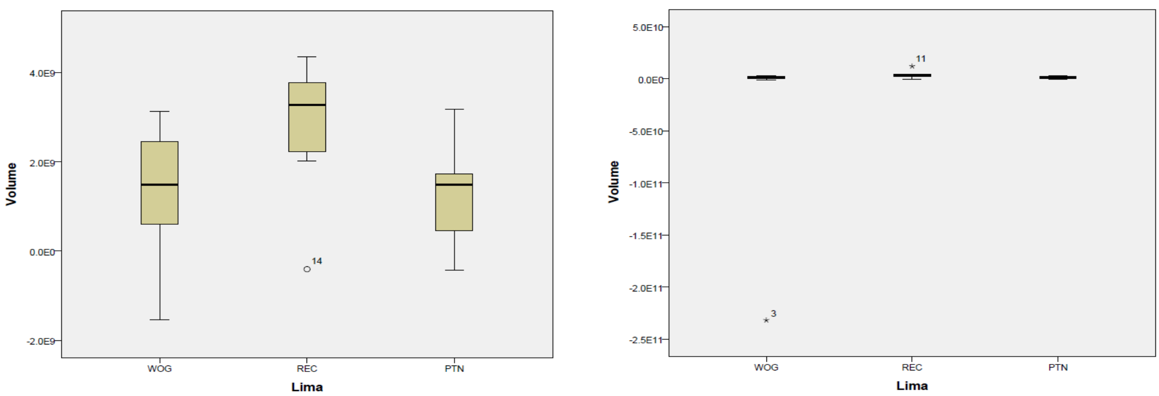
	Wave One Gold	Reciproc	ProTaper Next	*p*
Volume	5,98E+09 ± 2,62E+09	8,26E+09±3,42E+09	1,05E+10±7,43E+09	0,224
SMI	3,26 ± 1,00	3,18±0,87	3,28±0,58	0,625
Surface	7,47E+07 ± 2,17E+07	9,49E+07 ± 2,23E+07	2,91E+08 ± 3,63E+08	0,129
Area	4,54E+05 ± 1,94E+05	5,62E+05±2,86E+05	7,95E+05±5.95E+05	0,368
Diameter	280,32 ± 83,23	265,59±110,40	237,75±142,85	0,705

Table 1 - morphometric data of the root canal (mean ± standard deviation) before instrumentation; Statistically significant differences between groups before the preparation weren't recorded.

4.1 Volume (µm^3):

	Wave One Gold	Reciproc	Protaper Next	p
Before	5,98E+09 ± 2,62E+09	8,26E+09 ± 3,42E+09	1,05E+10 ± 7,43E+09	
Before - After	1,45E+09 ± 1,46E+09	2,75E+09±1,62E+09	1,28E+09 ± 9,86E+08	0,054
%	27,02 ± 25,35	37,79 ± 21,55	25,62 ± 34,15	

Table 2 - Absolute change and percentage of root canal volume (mean ± standard deviation). There's no statistically significant differences between groups in the volume after canal preparation.



Graph 1 – Volume box-plots; Left: after remove outliers; right: before removing outliers.

4.2 SMI

	Wave One Gold	Reciproc	Protaper Next	p
Before	3,26 ± 1,00	3,18 ± 0,87	3,28 ± 0,58	
Before - After	0,57 ± 1,09	1,00 ± 1,40	0,69 ± 0,81	0,717
%	26,38 ± 40,27	46,96 ± 85,29	18,18 ± 22,42	

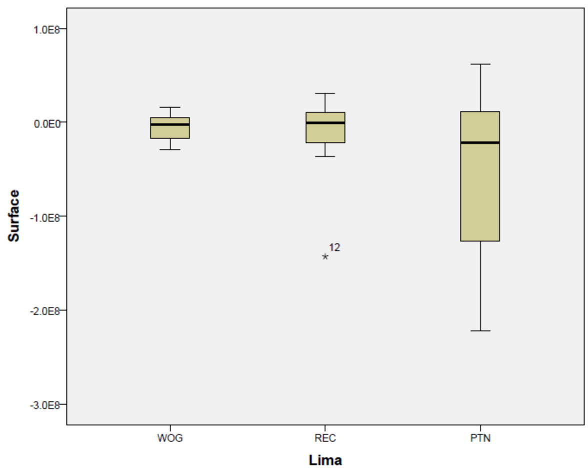
Table 3 - Absolute change and percentage SMI root canal (mean ± standard deviation).

No statistically significant differences between groups in change SMI after canal preparation.

4.3 Surface (μm^2):

	Wave One Gold	Reciproc	Protaper Next	p
Before	7,47E+07 ± 2,17E+07	9,49E+07 ± 2,23E+07	2,21E+08 ± 3,63E+08	
Before - After	-5,23E+06 ± 1,49E+07	9,72E+05 ± 2,04E+07	-5,50E+07 ± 8,94E+07	0,209
%	-5,53 ± 19,90	2,36 ± 20,82	-1,52 ± 51,55	

Table 4 - Absolute change and percentage of root canal surface (mean ± standard deviation). There's no statistically significant differences between groups in the surface change after canal preparation.

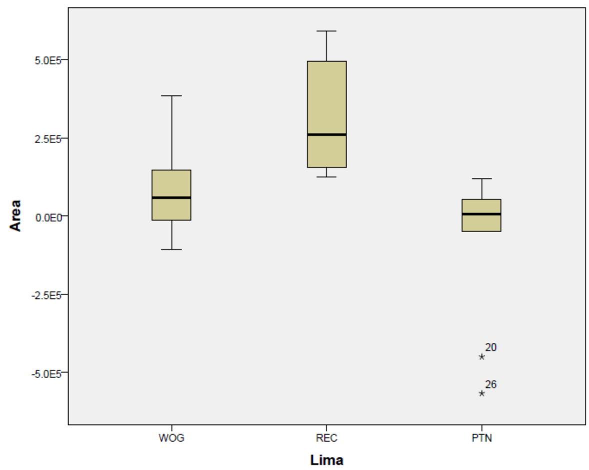


Graph 2 – Surface box-plot.

4.4 Area (μm^2)

		Wave One Gold	Reciproc	Protaper Next	p
Before		4,54E+05 ± 1,94E+05	5,62E+05 ± 2,86E+05	7,95E+05 ± 5,95E+05	
Before - After		7,62E+04 ± 1,40E+05	3,17E+05 ± 1,88E+05	2,76E+04 ± 5,61E+04	**0.005**
%		21,04 ± 33,49	68,62 ± 55,10	15,95 ± 32,82	
Multiple comparisons	**vs Wave One Gold**	-	**0,026**	0,588	
	vs Reciproc	**0,026**	-	**0,007**	
	vs Protaper Next	0,588	**0,007**	-	

Table 5 - Absolute change and percentage of root canal area (mean ± standard deviation). The area increase with Reciproc files was significantly greater than the area increase with WaveOne Gold ($p = 0.026$) or Protaper Next ($p = 0.007$).

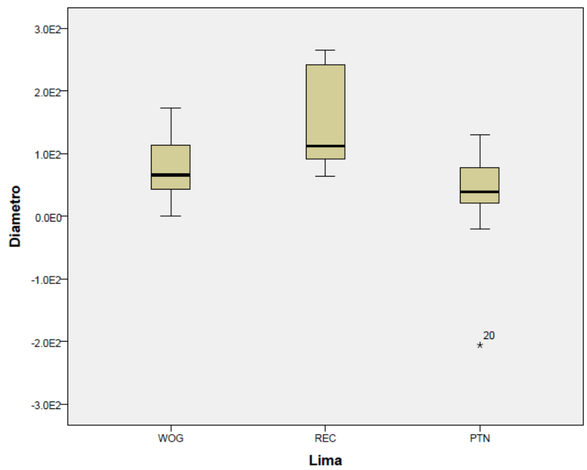


Graph 3 – Area box-plots.

4.5 Diameter (µm)

		Wave One Gold	Reciproc	Protaper Next	p
Before		280,32 ± 83,23	265,59 ± 110,40	237,75 ± 142,85	
Before - After		76,09 ± 54,76	152,16 ± 82,27	53,65 ± 48,35	**0.036**
%		34,37 ± 37,26	75,11 ± 69,47	29,56 ± 15,64	
Multiple comparisons	vs Wave One Gold	-	0,105	0,618	
	vs Reciproc	0,105	-	**0,032**	
	vs Protaper Next	0,618	**0,032**	-	

Table 6 - Absolute change and percentage of root canal diameter (mean value ± standard deviation). The increase of diameter after preparations with Reciproc files was significantly higher than the increase with ProTaper Next (p = 0.032). However, the difference between Reciproc and Wave One Gold was not statistically significant.



Graph 4 – Diameter box-plots.

5. DISCUSSION

The aim of this *ex vivo* study was to evaluate the mechanical shaping ability of 3 different file systems, A- WaveOne Gold^{TM}, B- Reciproc^{TM} and C- ProTaper Next^{TM}, comparing 5 parameters: canalar volume, SMI, surface, canalar area and diameter (average).

Our data revealed no differences between the three systems in the tridimensional parameters: volume, SMI and surface of shaping (p-value > 0,05). However, there are statistically differences in the canalar area and diameter**:**

- ✓ Area: The area increment with Reciproc^{TM} files was significantly greater than with WaveOne Gold^{TM} system ($p = 0.026$) or Protaper Next^{TM} ($p = 0.007$).
- ✓ Diameter: The increase of diameter after preparations with Reciproc^{TM} files was significantly higher than the increase with ProTaper Next^{TM} ($p = 0.032$). However, the difference between Reciproc^{TM} and Wave One Gold^{TM} was not statistically significant.

Structure Model Index (SMI) parameter makes possible to quantify the characteristic form of a three-dimensionally described structure in terms of the amount of plates and rod composing the structure. The SMI is calculated by means of three-dimensional image analysis based on a differential analysis of the triangulated bone surface. For an ideal plate and rod structure the SMI value is 0 and 3, respectively, independent of the physical dimensions. For a structure with both plates and rods of equal thickness the value lies between 0 and 3, depending on the volume ratio of rods and plates. The SMI parameter is evaluated by examining bone biopsies from different skeletal sites. The bone samples were measured three-dimensionally with a micro-CT system. Samples with the same volume density, but varying trabecular architecture can uniquely be characterized with the SMI. Furthermore, the SMI values were found to correspond well with the perceived structure type. The values range from 0 to 4, and the values 0, 3 and 4 correspond, respectively, to a plan, a cylinder and a regular ball (Hildebrand et al., 1997). Our SMI results (on average close to 4) reflected the settlement of the root canal walls after mechanical preparation, with no statistically significant differences between the systems. also reflecting the conical feature of the instruments used.

In previously studies, single-file reciprocating system strongly decrease the mean preparation time in comparison with multi-file rotational systems (Bürklein et al., 2012) and, so, the time available for chemical disinfection of the root canal systems is simultaneously increased, which is an advantage for Reciproc^{TM} and Wave One Gold^{TM} files. To compensate the inferior irrigation time in multiple-files systems, as ProTaper Next^{TM}, utilization of larger volumes of irrigant or activation of the irrigants, has been advised to improve chemical dissolution of residual debris (Bürklein et al., 2012).

Objective in root canal preparation is to develop a shape that tapers from apical to coronal, maintaining the original canal shape (Gergi et al., 2010). The disrespect of the original canal anatomy can lead the clinician to miss preparation objectives: remove remaining pulp tissue, eliminate microorganisms, remove debris and shape the root canal(s), so that the root canal system can be cleaned and filled (European Society of Endodontology, 2006). Thus, irrigation with antibacterial solutions is performed as complement to mechanical preparation and it depends largely on the ability of the irrigant to penetrate the full extent of the root canal system (Salzgeber et al., 1977). Irrigant penetration is influenced by the original anatomy of the root canal system as well as the final shape created through mechanical preparation (Gulabivala et al., 2005). Therefore, the size and taper of the apical instrumentation are important in order for the needle and the irrigating solution to reach the working length (Ellen et al., 2013). An increase in the taper of the root canal was shown to have a direct effect on irrigant flow, resulting in more efficient replacement and debridement in the apical part of the root canal, apart from allowing penetration of the needle closer to working length (Albrecht et al., 2004), which could be an advantage for Reciproc^{TM} and WaveOne Gold^{TM} systems that showed, in this study, an increase in the canalar diameter and area. In addition, apical preparation size was found to affect the extent of irrigant replacement, the shear stress on the canal wall and the pressure at the apical foramen. Root canal enlargement to sizes larger than 25 improved the performance of syringe irrigation. Adequate space between the needle and the canal wall should be ensured to allow effective reverse flow of the irrigant towards the root canal orifice (Boutsioukis et al., 2010). So in this case, although the 3 groups finished the mechanical preparations with instruments with a tip diameter equivalent to size 25, the canalar diameter don't increases equally between them. Possibly, due to the different taper that the systems have between each other: while ProTaper Next™ X2 file has a taper of 0.06 in the initial 3mm, WaveOne Gold™ Primary file has a initial taper of 0.07 and Reciproc™, has the greater cronicity, with a taper of 0.08 in the apical 3 mm.

The use of extracted teeth in endodontics research has the advantage of enabling, partially, the reproducibility of the clinical conditions (Nagy et al., 2008). However, the morphological variability of the root canal system in the same group of teeth, makes the sample standardization very complex (Hülsmann et al., 2008). Our sample, between the 3 groups, didn't recorded any significant anatomic differences before the mechanical preparation. Furthermore, two of the samples were excluded: sample #16 fractured during the analysis procedure in the micro tomography and the sample #20 had no canalar permeability. Both samples were from the group B in study (the Reciproc™ system), which has made this a shorter sample relative to the others (8 instead of 10 samples per group). In general, due to the difficulty in obtaining teeth within the inclusion criteria, one potential limitation of this study can be a result of a relatively small sample size (n total final = 28), however this is common to other µCT studies (Ribeiro et al., 2013; Peters et al., 2003).

An ideal technique for the study of root canal anatomy would be the one that is not only accurate, simple, nondestructive, but also and most importantly, feasible and reproducible in an in vivo scenario (Neelakantan et al. 2010; Zhang et al. 2011). On the other hand, in an ex vivo scenario, nondestructive micro-computed tomographic techniques (micro-CT) has gained popularity, because they provide accuracy, high-resolution, and can be used for detailed quantitative and qualitative measurements of root canal anatomy (Peters et al., 2000; Plotino et al., 2006). Micro-CT is a powerful tool for research and preclinical education in fundamental procedures of endodontic treatments, as well as for clinicians and researchers who desire to study dental anatomy in great detail (Plotino et al., 2006). One of the advantages of this method is that the dentist can observe the internal anatomy of teeth from different angles and it can facilitate endodontic instrumentation. Furthermore, with this technique it is possible to tilt and rotate the image while areas of interest were magnified (Grande et al., 2012). Micro-CT provides a better assessment of fine anatomical structures because of the possibility of using a higher exposure time (~40 min) and lower voxel size (19.6 lm) than CBCT, for example, (exposure time: 20 sec; voxel size: 120– 150 lm) during the scanning procedure. Additionally, the possibility of micro-CT devices to acquire imaging projections using a higher degree rotation of the specimen (360) in comparison with Planmeca CBCT unit (200) allowed the development of a more accurate and detailed 3D models of the root canal space. MicroCT offers exciting potential; however, current imaging times, are around 2hours per sample, the equipment is expensive and the 3-D reconstruction requires a high degree of computer expertise. In addition, the technique is not suitable for clinical use; notwithstanding the limited clinical applicability of micro-CT technology, this method has been proven to be the current reference method for the ex vivo studies, like this one, of root canal anatomy.

Additional studies on endodontic techniques and instruments taking into consideration the configuration of the root canals are required to provide more information and better endodontic instrumentation.

6. CONCLUSIONS

According to the results of the present investigation, the null hypothesis was rejected, because significant differences were obtained between the 3 file systems regarding their shaping ability in mesial roots extracted from humans mandibular first molars. Thus, based on the methodology used and the results obtained in this study, it may be conclude that:

✓ WaveOne Gold™, Reciproc™ and ProTaper Next™ showed similar shaping ability at the 3D canalar parameters: volume, SMI and surface;

- ✓ About 2D parameters, there was significantly higher increase in canalar area after preparation with Reciproc™ files comparing to WaveOne Gold™ and ProTaper Next™ (without statistically significant difference between those two systems). About the canalar diameter (the average), Reciproc™ and WaveOne Gold™ revealed a significant increase post instrumentation, superior to the ProTaper Next™ value;

- ✓ In general, we can admit that the system Reciproc™ was which produced major changes in the geometric conditions of the root canal, followed by WaveOne Gold™ and ProTaper Next™, respectively;

- ✓ Since WaveOne Gold™ modern files are on market, there are no articles or studies availing or comparing this system and so, the conclusions are limited.

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APPENDIX

a) Abbreviations

- NiTi: Nickel-Titanium
- 2D: Bidimensional
- 3D: Tridimensional
- SMI: Structure Model Index
- CT: Computerized tomography

b) Symbols

- %: Percentage
- ™: Unregistered trademark

c) Units

- rpm: Rotations per minute
- mm: Millimeters
- N: Newton
- µm: Micrometer
- mL: Milliliter
- kV: Kilovolts
- µA: Micro amperes
- ms: Milliseconds

d) Figure Index

e) Tables Index

f) Graphs Index

APPENDIX 2 - Tables of parameters observations (from µCT):

a) WaveOne Gold:

	VOLUME 3D ($\mu m3$)	
Sample	Before	After
1	1,20E+10	1,34E+10
2	3,09E+09	3,69E+09
3	2,40E+11	7,92E+09
4	5,62E+09	8,75E+09
5	6,84E+09	9,68E+09
6	4,79E+09	7,03E+09
7	3,25E+09	4,75E+09
8	5,32E+09	5,76E+09
9	6,50E+09	8,95E+09
10	6,41E+09	4,87E+09

	SMI 3D	
Sample	Before	After
1	3,4615	4,71
2	4,1624	4,32
3	2,8448	4,01
4	3,3841	3,7
5	2,8983	3,5967
6	2,0219	4,15
7	2,2673	4,0034
8	2,9315	2,96
9	3,1281	3,05
10	5,53	3,8299

	SURFACE 3D (µm2)	
Sample	Before	After
1	9,86E+07	9,63E+07
2	3,86E+07	4,38E+07
3	8,89E+07	6,80E+07
4	9,59E+07	7,91E+07
5	9,50E+07	1,05E+08
6	6,30E+07	7,93E+07
7	7,95E+07	5,01E+07
8	4,24E+07	3,98E+07
9	7,86E+07	8,35E+07
10	6,65E+07	5,01E+07

	AREA 2D (µm2)	
Sample	Before	After
1	8,69E+05	9,23E+05
2	2,25E+05	2,43E+05
3	5,25E+05	5,11E+05
4	3,89E+05	5,54E+05
5	5,08E+05	6,54E+05
6	3,36E+05	4,59E+05
7	2,05E+05	2,70E+05
8	6,05E+05	5,33E+05
9	4,09E+05	7,92E+05
10	4,72E+05	3,66E+05

	DIAMETER 2D (µm)	
Sample	Before	After
1	4,00E+02	4,60E+02
2	2,66E+02	2,80E+02
3	2,74E+02	3,87E+02
4	2,19E+02	3,67E+02
5	2,38E+02	3,07E+02
6	2,52E+02	2,95E+02
7	1,38E+02	3,11E+02
8	4,20E+02	4,82E+02
9	2,76E+02	3,54E+02
10	3,21E+02	3,21E+02

b) Reciproc:

	VOLUME 3D	
Sample	Before	After
11	5,61E+09	1,76E+10
12	8,95E+09	1,33E+10
13	6,66E+09	9,11E+09
14	1,38E+10	1,34E+10
15	4,86E+09	6,87E+09
16	Tooth broke in µCT	
17	4,92E+09	8,19E+09
18	8,73E+09	1,28E+10
19	1,25E+10	1,60E+10
20	Canal without permeability	

	SMI 3D	
Sample	Before	After
11	3,6308	4,41
12	3,8366	5,99
13	3,0073	2,43
14	1,4908	5,2
15	3,0304	4,09
16		
17	4,4578	4,17
18	3,1709	3,25
19	2,8155	3,87
20		

	SURFACE 3D	
Sample	Before	After
11	1,04E+08	1,35E+08
12	2,57E+08	1,14E+08
13	8,67E+07	8,77E+07
14	1,01E+08	6,53E+07
15	5,77E+07	6,72E+07
16		
17	1,06E+08	9,82E+07
18	8,09E+07	9,18E+07
19	1,28E+08	1,26E+08
20		

	AREA 2D	
Sample	Before	After
11	3,24E+05	9,14E+05
12	6,51E+05	7,76E+05
13	5,23E+05	6,63E+05
14	8,72E+05	1,33E+06
15	2,83E+05	4,72E+05
16		
17	3,09E+05	4,79E+05
18	4,60E+05	9,91E+05
19	1,07E+06	1,40E+06
20		

	DIAMETER 2D	
Sample	Before	After
11	1,80E+02	4,31E+02
12	1,21E+02	3,86E+02
13	2,56E+02	3,43E+02
14	4,48E+02	6,79E+02
15	2,78E+02	3,42E+02
16		
17	1,58E+02	2,78E+02
18	3,57E+02	4,60E+02
19	3,27E+02	4,23E+02
20		

c) ProTaper Next:

	VOLUME 3D	
Sample	Before	After
21	9,38E+09	1,11E+10
22	6,62E+09	8,20E+09
23	2,21E+09	4,09E+09
24	1,08E+10	1,04E+10
25	5,94E+09	6,35E+09
26	2,37E+10	2,69E+10
27	1,05E+10	1,15E+10
28	2,21E+10	2,36E+10
29	1,56E+09	3,00E+09
30	1,21E+10	1,25E+10

	SMI 3D	
Sample	Before	After
21	3,46	5,6
22	3,45	8,71
23	2,5056	3,65
24	3,3779	4,09
25	3,9292	4,07
26	2,3987	2,72
27	3,8975	3,51
28	2,9207	4,58
29	2,9302	3,12
30	3,9688	4,3

	SURFACE 3D	
Sample	Before	After
21	9,83E+07	8,33E+07
22	8,28E+07	1,45E+08
23	3,66E+07	5,01E+07
24	4,04E+08	2,70E+08
25	1,71E+08	1,43E+08
26	1,04E+09	9,22E+08
27	1,28E+08	5,80E+05
28	8,48E+08	6,26E+08
29	1,63E+07	2,73E+07
30	8,24E+07	8,79E+07

	AREA 2D	
Sample	Before	After
21	5,88E+05	6,79E+05
22	1,04E+06	5,86E+05
23	2,32E+05	2,85E+05
24	6,42E+05	5,93E+05
25	3,66E+05	3,77E+05
26	1,75E+06	1,73E+06
27	5,81E+05	5,80E+05
28	1,88E+06	1,31E+06
29	1,28E+05	2,47E+05
30	7,60E+05	7,72E+05

	DIAMETER 2D	
Sample	Before	After
21	3,20E+02	4,50E+02
22	3,96E+02	1,90E+02
23	1,94E+02	2,72E+02
24	9,45E+01	1,33E+02
25	1,19E+02	1,50E+02
26	8,17E+01	1,03E+02
27	2,72E+02	3,16E+02
28	9,23E+01	1,32E+02
29	3,21E+02	4,43E+02
30	4,86E+02	4,65E+02

APPENDIX 3

Image example from micro CT (Sample nr. 3 - post instrumentation):